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THEORY OF THE CONTACT BETWEEN TWO SEMICONDUCTORS  
WITH DIFFERENT TYPES OF CONDUCTIVITY

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## Introduction

Systematic experimental investigations of the contact of various pairs of semiconductors were conducted by A. V. Ioffe (ZhTF, Vol 18, p 1498, 1948). He observed two main phenomena: (1) the contact possessed a rectifying action; (2) the resistance  $R_p$  of a pair of semiconductors in contact with each other for small applied voltages  $V$  was considerably greater, even in the conducting direction, than the sum of the resistances  $\Sigma R$  of both semiconductors, as measured separately between metal electrodes. For  $V$  tending toward zero, the resistance in the conducting and nonconducting directions tended toward one and the same limit. For increasing  $V$  in the conducting direction, the contact resistance  $R_p$  quickly and sharply fell to  $\Sigma R$ ; but for increasing  $V$  in the nonconducting direction,  $R_p$  also fell, but rather slowly and weakly, and sometimes remained constant or increased slightly.

Both phenomena were observed especially when the semiconductors possessed differing types of conductivity, one being properly electron conductivity and the other being hole conductivity. In this case the difference of their work functions ensured the formation a close-contact layer poor in current carriers. The work function of an electron semiconductor was less than the work function of the hole semiconductor. For example, in the case of the pair  $\text{TiO}_2$  (electron) and  $\text{Cu}_2\text{O}$  (hole), the ratio  $R_p/\Sigma R$  reached  $10^4$ ; the maximum coefficient of rectification was also  $10^4$ . The conducting direction corresponded to the negative voltage applied to an electron semiconductor.

In the case of semiconductors with different types of conductivity but with contact difference of potential which does not ensure a layer deficient in carriers, the resistance was observed also to increase 4 to 6 times. Rectification was weaker.

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In the case of semiconductors of the same type and with contact difference of potentials, the resistances and rectification were observed to increase, but much more weakly than in semiconductors of different types. The ratio  $R_p/\Sigma R$  did not exceed 600, and the coefficient of rectification was 100.

The theory of contact of two semiconductors with differing conductivity types was proposed by B. I. Davydov (ZhETF, Vol 8, p 3, 1938; and DAN SSSR, Vol 20, p 279, 1938). In this theory, however, he did not study the contact difference of potentials between the semiconductors nor the distortion in the zones close to the contact; he disregarded the space charge.

The space charge and distortion in the zones close to the contact were studied in the theories of B. Bickhntsev and B. I. Davydov (DAN SSSR, Vol 21, p 22, 1938) and S. I. Pekar (ZhETF, Vol 9, p 534, 1939), but these theories related only to the contact between two semiconductors with the same type of conductivity; the contact difference of potentials also was not taken into account by them.

In later works of B. I. Davydov (ZhETF, Vol 9, p 451, 1939; Vol 10, p 1342, 1940), and also in a second work of S. I. Pekar (ZhETF, Vol 10, p 1210, 1940), and in the theory of Schottky and Spence (Veroff, Siemens Werke, 18, 1, 1938) and others, the contact difference of potentials and the distortion caused by it in the zones near the contact of semiconductor and metal were studied. With certain variations these theories can be adapted to the contact of two semiconductors, however, none of these theories can explain the strong rectification observed near the contact of an electron semiconductor with a hole semiconductor. They do not explain even the effect, observed in experiments, of resistance increase of a pair of semiconductors of different type, when the nonconducting layer causing the contact difference of potential is absent.

These latter circumstances force one to assume that at the contact of an electron semiconductor with a hole semiconductor there is formed a nonconducting layer of a special nature, not considered in the theories of B. I. Davydov and others. The present article gives the theory of such a layer. It is shown that the contact must possess great resistance and considerable rectifying action. The influence of the contact difference of potentials is taken into consideration.

This article also takes into consideration the current flowing through the contact. The formula obtained allows one to construct the volt-ampere characteristic, which in the conduction and in the nonconducting regions agrees well with the characteristic obtained empirically.

This theory can be applied also to an explanation of the action of technical solid rectifiers, since the hypothesis has been repeatedly expressed by A. V. Ioffe and Davydov that in these rectifiers the rectification occurs not in the boundary of the semiconductor with the metal but in the boundary of the two layers of the semiconductor with different type of conductivity. Actually, the rectifying action of solid rectifiers is considerably stronger than that predicted by the theory of metal-semiconductor contact.

[The main headings, and brief summaries of the remaining sections of the article follow.]

#### 1. Physical Bases of the Theory

The current density  $j$  is related to the contact potentials  $V_1, V_2$ , temperature  $T$ , field strength  $E$ , charge density  $n$ , etc., according to the Fermi distribution.

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2. Calculations in the Zero Approximation

Approximate expressions are found for the voltage drops  $V_1$ ,  $V_2$ ,  $V_3$ , and for the concentration of electrons  $n$ , and holes  $n_2$ , etc.

3. Calculation of the Current Passing Through the Contact

The transparency  $D$  of the gap and the indicated current in terms of  $n_1$ ,  $n_2$ ,  $T$ ,  $V$ , etc., are given.

4. Analysis of the Expression Obtained for the Current

The ohmic drop in potential was not considered in this work, only the diffusional drop, just as the ordinary theories of rectifiers do not consider the diffusional drop but only the ohmic potential drop. The ohmic potential drop can play a large role for large currents.

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